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Impact of climate change on groundwater recharge and base flow in the sub-catchment of Tekeze basin, Ethiopia

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ABSTRACT

The impacts of climate change are significant on both surface and groundwater resources. However, little attention has been given to the effect of climate change on groundwater resources. Therefore, the present study is concerned with the effect of climate change on groundwater recharge and base flow in Tekeze sub-catchment in Ethiopia. The future climate variables were obtained from Coordinated Regional Climate Downscaling Experiment (CORDEX) Africa program for Representative Concentration Pathways (RCPs) of RCP 2.6 and RCP 4.5 scenarios. The Mann-Kendall test and Sen's slope estimator were used for trend detection using XLSTAT software package. Further, the downscaled and bias corrected precipitation, temperature, and potential evapotranspiration were provided to the WetSpa model to simulate future water balance components. The results indicated a decreasing trend in annual rainfall and an increasing trend in average temperature and evapotranspiration for selected scenarios. At the catchment level, precipitation decreases by 20% for both RCP 2.6 and RCP 4.5 scenarios, and actual evapotranspiration shows 0.4% and 8.1%increment for RCP 2.6 and RCP 4.5, respectively. Consequently, the groundwater recharge decreases by 3.4% for RCP 2.6 and 1.3% for RCP 4.5. Base flow will also decrease by 1.5%and 0.55% for RCP 2.6 and RCP 4.5, respectively. The results of this study would help policymakers, scientists, government officials and local stakeholders in planning and management of the surface and groundwater resources in the Ethiopian regions.

1. Introduction

Water is indispensable for life. However, its availability in sustainable quality and quantity is threatened by many factors, of which climate plays a leading role (Kumar, 2012). Climate change can have profound effects on the hydrologic cycle through precipitation, evapotranspiration and soil moisture with increasing temperature. However, the extra precipitation will be unequally distributed around the globe. Some parts of the world may see significant reductions in precipitation or major alterations in the timing of wet and dry seasons. Therefore, knowledge on the climate change impacts on different hydrological components and water resources is becoming more crucial (IPCC 2001 cited in Ranjan et al., 2006; Kumar, 2012; Kumar, 2013).

The IPCC (2013) report suggests that climate change has the potential to deteriorate the groundwater availability, water quality, and water supplies. Herrera-Pantoja and Hiscock (2008) concluded that future climate may present a decrease in potential groundwater recharge that will increase stress on local and regional groundwater resources. In understanding the consequences of climate change on groundwater resources and water balance system (especially, precipitation and evapotranspiration), an important component that needs to have due attention is the influence of anthropogenic factors on groundwater recharge and base flow. Current research has mainly focused on surface water resources and less attention was given on the potential impacts of climate change on groundwater system. The impacts of climate change on groundwater are profound and need to be explored more, especially in African regions, where most people depend on groundwater for different purposes (Taylor and Howard, 1996; Kulabako et al., 2007; Abiye, 2016).

Ethiopia has ample water resources potential of which groundwater has a significant role (MoWIE, 2017). The approximate amount of annual groundwater recharge of Ethiopia is estimated about 28,000 Mm^3 (Obuobie, 2008; MoWIE, 2017). Awulachew et al. (2007) showed that the groundwater potential of the country is more than the estimated amount. Most of the groundwater resources are mainly utilized for irrigation, domestic and industrial purposes. Groundwater is an important water resource and needs more attention on its vulnerability to overexploitation (Dey et al., 2017), pollution and, especially, climate

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change. Both reliable prediction of changes in the major climatic variables and accurate estimates of groundwater recharge are required to quantify the impact of climate change on groundwater resources (Jyrkama and Sykes, 2007; Kumar, 2012). The information on groundwater recharge is necessary for sustainable management of water resources (Tilahun and Merkel, 2009) and fluid and contaminant transport modeling within the subsurface (Healy, 2010).

Groundwater recharge is a function of climatic factors, local geological formation, topography and land use types of the area under consideration (Dragoni and Sukhija, 2008). This has a direct relationship with precipitation and physiochemical properties of soils. As precipitation varies with climate change due to temperature and evapotranspiration, there is possibility of variation in groundwater recharge. Due to variations in the distribution of rainfall, drought is a common phenomenon in Ethiopia (Gebrehiwot and Veen, 2013). Earlier, Meze-Hausken (2004) also reported the perception of climate variability and meteorological drought and further, its impact on decreased water availability in Northern Ethiopia. There are several studies reported concerning drought phenomenon in Ethiopia in recent past (e.g., Gedif et al., 2014; Legesse and Suryabhagavan, 2014; Suryabhagavan, 2017). Evidently, Ethiopia in general and the study area in particular, have suffered from shortage of food due to erratic rainfall (Lewis, 2017) and unsustainable use of water resources (Gebrehiwot and Veen, 2013).

Many researchers have conducted studies to investigate the climate change impacts on groundwater and recharge in and around Tekeze river basin (Walraevens et al., 2009; Beyene et al., 2011; Tesfagiorgis et al., 2011; Gebremeskel, 2015; Haile, 2015). However, most of the earlier studies were focused on the effect of land use/land cover change on hydrological processes including groundwater and the rate of groundwater recharge in the basin (e.g., Gebremicael et al., 2013; Ashenafi, 2014; Haregeweyn et al., 2015; Welde and Gebremariam, 2017). Haile (2015) estimated groundwater recharge and potentials under changing climate conditions in Werii watershed in Tekeze river basin. However, the study is limited to IPCC A1B and B1 scenarios. The impact of climate change on groundwater recharge and base flow were not considered. Very few studies were done on groundwater recharge and base flow (e.g., Zomlot et al., 2015). Therefore, studying the basins groundwater characteristics in terms of groundwater recharge and base flow and climate change impact is essential. The main objective of this study is to estimate the effect of climate change on groundwater recharge and base flow using climate and hydrological models in the Tekeze River basin. The trends of major climate variables such as precipitation, evapotranspiration, and temperature affecting groundwater recharge in the Tekeze sub-catchment were also assessed using Mann-Kendall (MK) test. The results from this study can be utilized by local stakeholders and water resources managers for water resource planning and management in the catchment.

2. Materials and methods

2.1. Study area

Tekeze river basin is located in the north-western part of Ethiopia. Specifically, the Tekeze sub-catchment is located southeast of the basin in the geographical location of 11°39′32.17″ and 13°27′15.96″ East longitude, and 37°33′27.63″ and 39°40′7.24″ North latitude (Fig. 1). The catchment lies in both Amhara and Tigray regional states covering a total surface area of 29405 km^2. The elevation of the catchment varies from 1028 to 4536 m above mean sea level (m.a.s.l.) (Fig. 1). The slope of the watershed varied between 0 to 78.2% (Fig. 2a). The Tekeze River contributes nearly 13% of the total annual flow of the Nile waters during the dry season and 22% during the flood season (Degefu, 2003).

The Tekeze basin has highly variable rainfall concentrated in one rainy season (June to September) separated by relatively long dry seasons. The mean annual rainfall in the Tekeze basin ranges from 600 mm to 1300 mm. The average maximum and minimum temperatures are around 24.8 °C and 12.5 °C, respectively. There is a high temporal variation of rainfall and high variation between daily maximum and minimum temperatures in the study area. However, the seasonal variation of temperature is less than the diurnal variation. The major land use/land cover (LULC) classes in the basin include intensively cultivated land (7%), sparsely cultivated (58%), open woodland (12%), open grassland (5%), sparsely vegetated (0.2%), complex land (15%), and others (2.8%) (Fig. 2b). Based on the USDA soil classification system, five major soil types are identified in the catchment namely sandy loam, silty clay, silt, silty loam, and clay. Silty loam, clay, and silt are the dominant soil types of the catchment area (Fig. 2c).

2.2. Data used

The meteorological data such as precipitation, minimum and maximum temperature from the years 1994–2013 were collected from the Ethiopian National Meteorological Agency (NMA). Precipitation data were utilized from six meteorological stations (Gonder, Lalibela, Mitsebri, Maichew, Mekelle, and Samre). The streamflow data of the catchment at the Embamadre gauging station was collected from the Ethiopian Ministry of Water, Irrigation, and Energy (MoWIE). The digital elevation model (DEM) of 30 m resolution was obtained from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Elevation Model (GDEM) version 2 databases (http://aster.usgs.gov) which is a product of Ministry of Economy, Trade, and Industry (METI) of Japan and National Aeronautics and Space Administration (NASA) agency of United States of America. Slope map of the watershed was derived from the DEM (Fig. 2a). The soil, and LULC map were collected from the Ethiopian land cover data set. Land cover data was derived from the original raster based global land cover of Africa archive (http://www.africover.org./index.htm) of the year 2008 (Fig. 2b and c). Initially, rainfall data was subjected to data quality checks such as estimation of missing rainfall, homogeneity and inconsistencies in the records by using statistical methods. For this study, missed data (Table 1) was filled by using meteorological stations located in the nearby catchment through Normal ratio and distance power methods following the approach suggested by Subramanya (1998) depending on the percentage of missed data available for each station. The double mass curve method was applied for checking consistency in the data among the selected meteorological stations and data were found to be consistent. Thiessen polygon method was utilized to estimate the areal precipitation of the Tekeze sub-catchment.

The daily large scale RCM predictors from regional climate model REMO developed at the Max-Planck Institute for Meteorology (MPIM) in Hamburg, Germany (Jacob, 2001) were used to simulate the future climate changes. Downscaled rainfall and temperature (minimum and maximum) projected climate data for the period 1951–2100 were obtained from CORDEX-Africa database at a spatial resolution of 55 km (0.44° × 0.44°) for RCP 4.5 and RCP 2.6 scenarios. This data was used from Coupled Model Inter-Comparison Project Phase 5 (CMIP5) of IPCC fifth assessment report. The future climate change parameters on daily basis for the period of 1951–2100 for rainfall and temperature (minimum and maximum) data on a grid basis were collected from IWMI. The selected RCP data were subjected to bias corrections. The selected study area was covered with six RCM grid cells. RCP 2.6 scenario represents emissions of greenhouse gases (GHG) and air pollutants and measured peak emissions during 2010–2020 and declines substantially thereafter. While, the RCP 4.5 scenario represents a range of technologies and strategies for reducing GHG emissions until 2100 (van Vurren et al., 2011). For daily rainfall and temperature, future scenarios were considered for two different periods of near–term (2020–2049) and mid–term (2050–2079).

2.3. Methods

The conceptual framework of the study is presented in Fig. 3 and

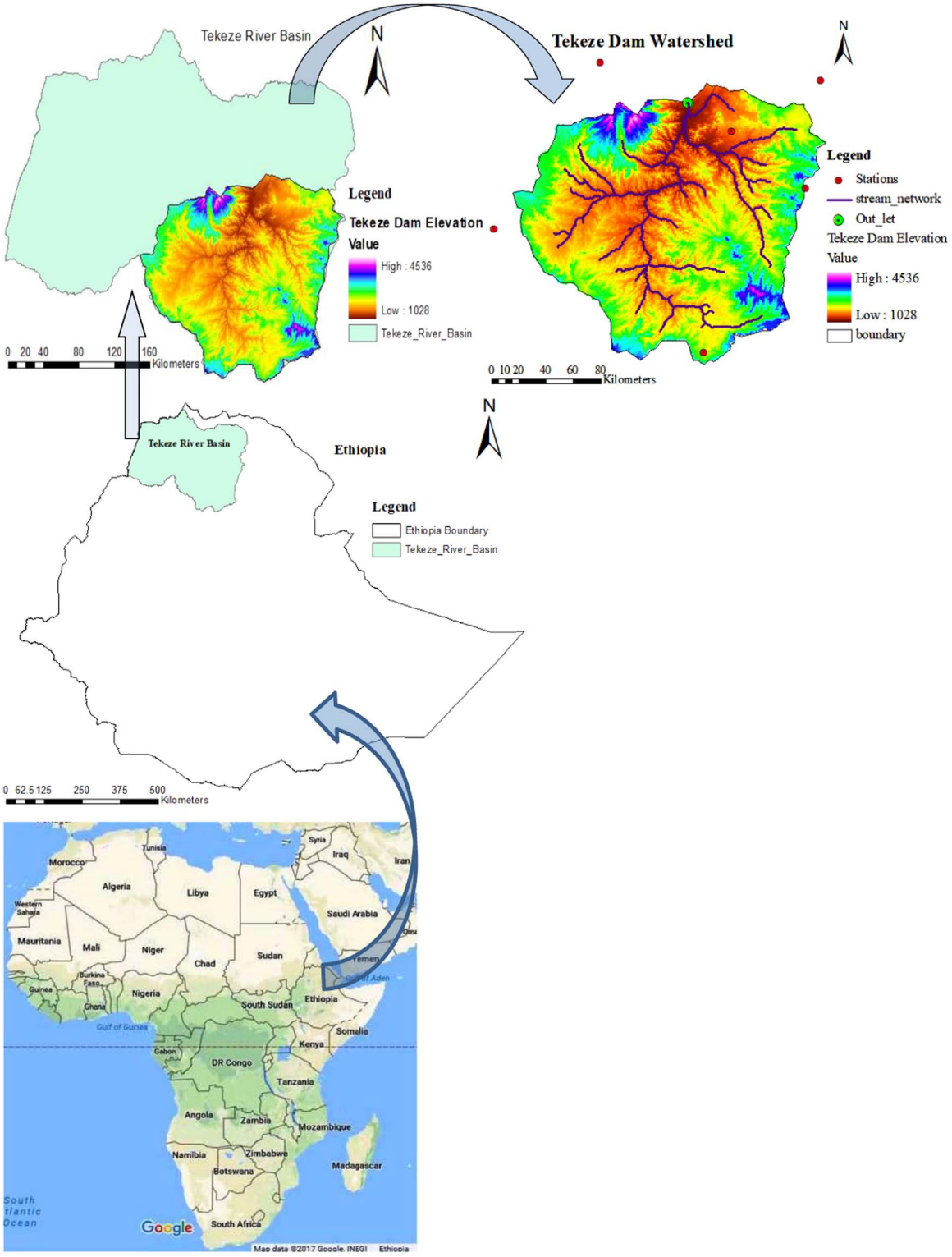

Fig. 1. Location of the study area Tekeze Dam catchment in Ethiopia.

discussed in the subsequent sections.

2.3.1. Bias correction

The bias corrections are necessary since climate models often exhibit systematic error (biases) which are caused as a result of limited spatial resolution, simplified physics and thermodynamic processes, numerical schemes or incomplete knowledge of climate system processes (http://ccafs-climate.org/bias_correction/). Therefore, bias correction is applied to avoid overestimate or underestimate of the downscaled variables. In this study, both linear and non-linear bias correction methods were used for correcting daily temperature and precipitation data. Leander and Buishand (2007) used a power transformation function, which corrects the coefficient of variation (*CV*) and the mean. In this nonlinear correction method, each daily precipitation amount, *P*, is being transformed to a corrected *P** using the equation:

$$P^* = aP^b \quad (1)$$

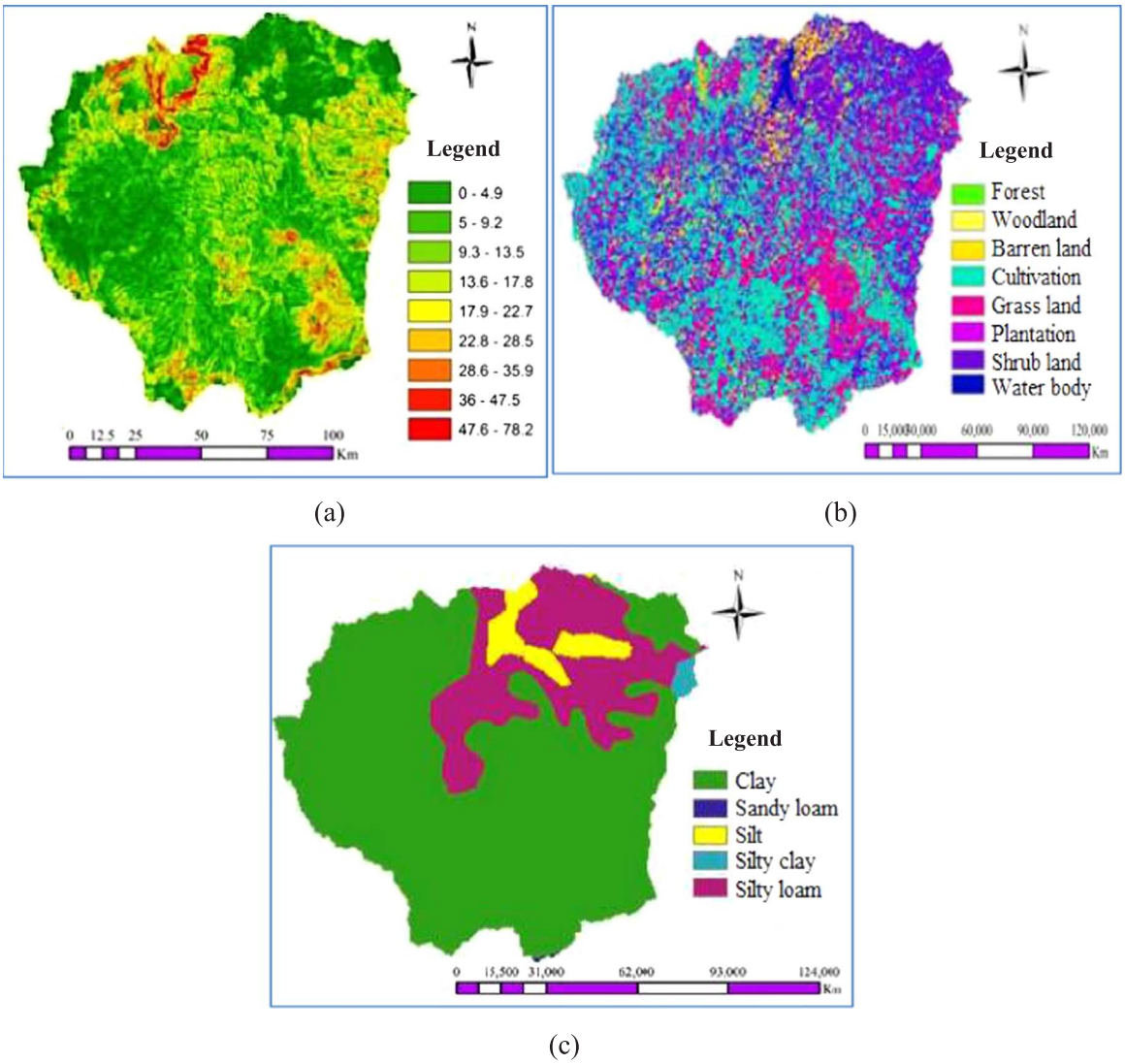

Fig. 2. The spatial input database for WetSpa model such as a) slope, b) soil map and c) land use/land cover (the year 2008) of the study area.

Table 1
Percentage of the missed data of the selected six stations.

No.	Station name	Data type	Missed data (%)
1	Gonder	Temperature, Rainfall	5.35, 10.64
2	Laibela	Temperature, Rainfall	0.23, 1.80
3	Maichew	Temperature, Rainfall	7.10, 15
4	Mekelle	Temperature, Rainfall,	0.25, 11.20
5	Samre	Temperature, Rainfall,	8.52, 18.36
6	Mitsebri	Temperature, Rainfall	5.23,20.50

where P^* is the simulated data in the projection period; 'a' and 'b' are the parameters obtained from calibration in the baseline period and subsequently applied to the projection period. These parameters are determined by matching the mean and CV of the simulated data with the observed data.

For temperature, monthly systematic biases were estimated for the baseline period (1994–2005) by comparing RCP outputs with the observed temperature. The monthly mean bias corrections were made according to Eq. (2) (Ho et al., 2012).

$$T_c = T_{om} + \frac{\partial_o}{\partial_r}*(T_r - T_{rm}) \quad (2)$$

where T_c = bias corrected future RCP temperature
T_{om} = mean of observed temperature in base period
T_{rm} = mean of RCP temperature in base period
T_r = RCP temperature of base period
∂_r and ∂_o = the standard deviation of the daily RCP output and observations in the reference period, respectively.

2.3.2. Estimation of potential evapotranspiration (PET)

After the bias correction for daily minimum and maximum temperature, potential evapotranspiration was estimated for use in the WetSpa (Water and Energy Transfer between Soil, Plants and Atmosphere) model. The *PET* time series data were calculated using the Hargreaves equation (Allen et al., 1998).

$$PET = 0.0023(T_{mean} + 17.8)(T_{\max} - T_{\min}) \times 0.5R_a \quad (3)$$

where, PET is the potential evapotranspiration (mm/day); T_{mean}, T_{max} and T_{min} are average, maximum and minimum temperature (°C) values, respectively; R_a is extraterrestrial radiation (mm/day). The corrected average daily *PET*, precipitation, and observed stream discharge were provided as an input for the WetSpa model to simulate the hydrologic water balance processes. These climate data were simulated for the future climate change scenarios.

2.3.3. Trend analysis

The assessment of spatio-temporal trends is important for many

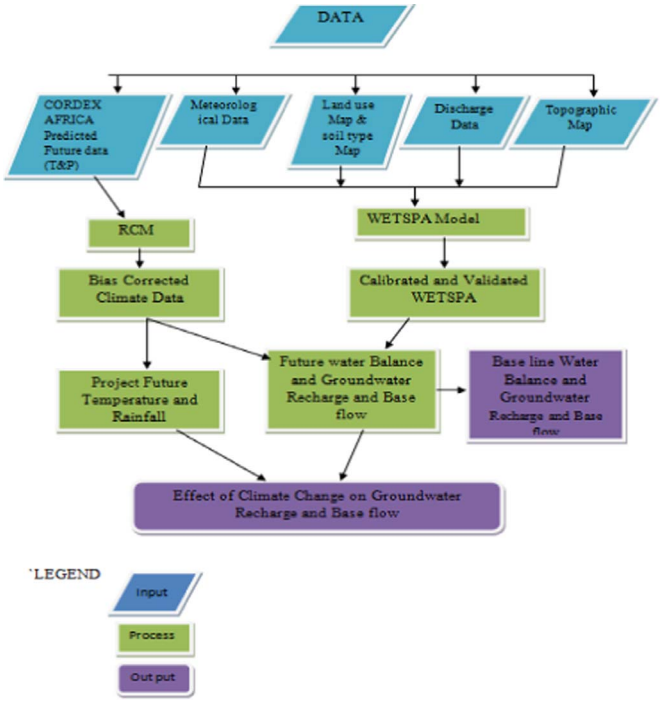

Fig. 3. Conceptual framework of the study.

environmental studies and monitoring programs (ITRC, 2013). For this study, trend analysis was done using non-parametric Mann-Kendall (MK) test. This is a statistical test widely utilized for the trend detection in climatological variables (e.g., Pingale et al., 2014; Seyoum et al., 2015; Pingale et al., 2016) and in hydrologic time series analysis (Yue and Wang, 2004). There are two advantages of MK test. First, it is a non-parametric test and does not require the data to be normally distributed. Second, the test has low sensitivity to abrupt breaks due to heterogeneous time series (Tabari et al., 2011). In fact, this test statistic is applied to test the null hypothesis (H_o) regarding the existence of trends in time series data. If $|Z_s| \geq Z_{\alpha/2}$, where α represents the significance level (e.g. 5% with $Z_{0.025} = 1.96$) then the null hypothesis is invalid implying that the trend is significant (Motiee and McBean, 2009). If p-value less is than the significance level ($\alpha = 0.05$), the null hypothesis (H_o) is rejected (statistically significant), while for p-value greater than the significance level ($\alpha = 0.05$), H_o is accepted (statistically non-significant) (Onoz and Bayazit, 2012). Failing to reject H_o does not mean that there is no trend. Rather, it is a statement that the evidence available is not enough to conclude on the existence of trends (Helsel and Hirsch, 2002). The positive and negative values of the S statistic indicate upward and downward trends, respectively. The XLSTAT version 2015 software was used to perform the statistical MK test analysis. The null hypothesis is tested at 95% confidence level for precipitation, temperature and evapotranspiration data for the six meteorological stations. Further details about the MK test can be found in Pingale et al. (2016).

2.3.4. Groundwater recharge and base flow estimation

2.3.4.1. Description of WetSpa model. WetSpa is a physically based distributed hydrological model for predicting the Water and Energy Transfer between Soil, Plants, and Atmosphere on regional or basin scale and daily time step, developed in the Vrije Universiteit Brussels, Belgium (Batelaan et al., 1996; Wang et al., 1996). It is one of the modeling packages used for simulating hydrologic processes under changing climateconditions. Different researchers (e.g., Adem and Batelaan, 2006; Woldeamlak et al., 2007; Nyenje and Batelaan, 2009; Jaroslaw and Batelaan, 2011; Haile and Kassa, 2015; Yenehun et al., 2017) have investigated association between different hydrological processes and groundwater recharge considering the impacts of climate change using the WetSpa model.

Historical hydro-climatic and other data such as precipitation, minimum and maximum temperature, potential evapotranspiration, streamflow, DEM, land use and soil type were used as an input for this model. The river flow hydrograph, soil moisture, infiltration rates, groundwater recharge, surface water retention and runoff are considered as the main outputs of the WetSpa model (Liu and De Smedt, 2004; Nyenje and Batelaan, 2009). The water balance of the root zone is considered as a key factor controlling runoff, interflow and groundwater recharge and is estimated for each grid cell as:

$$D\frac{\Delta\theta}{\Delta t} = P - I - S - E - F - R \tag{4}$$

where D is the root zone depth [L]; $\Delta\theta$ is the change in soil moisture content [L^3/L^3]; Δt is the time interval [T]; P is the precipitation [L]; I is the initial abstraction (interception and depression losses) [L]; S is the surface runoff [L]; E is the actual evapotranspiration [L]; F is the interflow [L] and R is the percolation out of the root zone [L]. The percolation out of the root zone recharges the groundwater storage (SG) [L], which then contributes to groundwater discharge forming the base flow of a stream (Liu and De Smedt, 2004). Base flow is a primary element in groundwater studies, which explains the nature of water movements in the subsurface (Gu et al., 2008).

Recharge is calculated using the hydraulic conductivity and effective saturation (Brooks and Corey, 1966):

$$R = K_s\left(\frac{\theta - \theta_s}{\theta_s - \theta_r}\right)^{(2+3B)/B} \tag{5}$$

where R is the recharge or percolation (mm); K_s is the saturated soil hydraulic conductivity (mm/h); θ is the soil moisture content (m^3/m^3); θ_s is the saturated soil moisture content (m^3/m^3); θ_r is the residual moisture content (m^3/m^3); B is the pore size distribution index, dimensionless. These values for recharge estimation were obtained based on the identified soil textural class in the study area and provided to the model (Cosby et al., 1984; Rawls et al., 1982 cited in Liu and De Smedt, 2004).

The base flow is simulated at the sub-catchment level using a lumped linear reservoir approach (Liu and De Smedt, 2004),

$$Q_{g(t)} = C_g\left(\frac{SG_{(t)}}{1000}\right) \tag{6}$$

where $Q_{g(t)}$ is the base flow (m^3/s); $SG_{(t)}$ is the groundwater storage (mm) and C_g is the groundwater flow recession constant (m^2/s).

2.3.4.2. WetSpa model set up. Gridded model parameters were estimated derived from topography, land use and soil data of the catchment along with attribute lookup tables in dbf format. Hydrological characteristics of the watershed such as slope, hydraulic radius, flow direction and flow accumulation, stream network and order, and sub-catchments were delineated using the DEM. The parameters such as hydraulic conductivity, pore size distribution index, plant wilting point porosity, field capacity, and residual moisture content for each grid cell were estimated from the soil map. Similarly, Manning's roughness coefficient, interception storage capacity and root depth parameters were calculated from the land use/land cover map (Tables 2 and 3).

An attribute lookup table containing elevation, soil and land use maps were derived to provide grids of potential runoff coefficient and depression storage capacity of the watershed. The instantaneous unit hydrograph (IUH), travel time to the basin outlet, grids of flow velocity and standard deviation were generated at the final time step. The parameter values that are taken as a threshold value and derived from other parameters and constants are listed in Table 2. In order to run the WetSpa model, the input base maps was provided 800m grid cell size with an average of 287 rows and 248 columns.

Table 2
Main calibration global parameters and it's common threshold values of the WetSpa model.
Source: (Liu and De Smedt, 2004).

Parameter	Description	Unit	Parameters	Unit	Value
Ki	Interflow scaling parameter	–	Stream network delineating threshold	Cells	10
Kg	Groundwater recession coefficient	–	Sub-catchments determining threshold value	Cells	1000
K_ss	Relative soil moisture	–	Upstream drained area by a particular cell	km^2	> 0.1
K_ep	Correction coefficient for PET	–	Sub catchments	Total	33
GO	Initial groundwater storage	Mm	Average sub-catchment area	km^2	909.1
G_max	Maximum groundwater storage	Mm	Average hydraulic radius at upland cells	Meter	0.005
TO	Base temperature for estimating snow melt	°C	Average hydraulic radius at outlets	Meter	1.5
K_snow	Degree day coefficient for calculating snow melt	mm/mm/°C/day	Time of concentration	Hour	91
K_rain	Rainfall degree day coefficient	mm/mm/°C/day	Mean travel time for entire watershed	Hour	23
K_run	Surface runoff coefficient	–	Manning's coefficient for lowest order	$m^{-1/3}$ s	0.055
P_max	Threshold rainfall intensity	mm/day	Manning's coefficient for highest order	$m^{-1/3}$ s	0.025
			Impervious area within an urban cell	%	30

Table 3
Global model parameters and calibration result for the catchment (Liu and De Smedt, 2004).

Parameter	Value range	Calibration result
Ki	0–12	3.21
Kg	0–0.06	0.045
K_ss	0–2	1.04
K_ep	0–2	0.5
GO	0–100	15
G_max	0–3000	17.41
TO	0–1	−1
K_snow	0–10	−1
K_rain	0–0.05	−1
K_run	0–5	3.5
P_max	0–500	250

2.3.4.3. Calibration and validation. The important global calibration parameters of WetSpa model with their measurement units are presented in Table 3. Where, K_i is a parameter for reflecting the organic matter in the root zone associated with soil hydraulic conductivity. K_g is a global parameter for reflecting catchment's groundwater recession regime and *K_ss* is related to field capacity for soil moisture content. Similarly, potential evapotranspiration is related with a *K_ep* and *G0*. The *G_max* is dependent on groundwater depth and *K_run* is an exponent for reflecting the effect of small rainfall intensity on surface runoff. *P_max* is a modeling time-dependent threshold for rainfall intensity (Liu and De Smedt, 2004). Since snow melting and accumulation did not happened in the catchment, temperature data were not utilized as an input for the modeling process. Therefore, the global parameters such as such as *TO, K_snow* and *K_rain* were set to a negative value (−1) so that they did not affect the model result.

The calibration and validation steps were carried out to investigate the performance of the model. The hydro-meteorological data such as daily precipitation, evapotranspiration, and runoff were divided to use for independent calibration (1995–2001) and validation (2002–2004) processes. Hence, data collected within similar timescale for all the meteorological parameters and spatial data from the base map including land use, and soil texture were used for calibration and validation of the model (Table 2). Model calibration was carried out by repetitive trial and error method and fine-tuning the global parameters within the acceptable range (Table 3). The calibration and validation results were also compared with observed values using model performance indicators. After the calibration of the WetSpa model, the water balance components were calculated based on the measured input parameters. The water balance components simulated for the catchment includes total interception, surface runoff, infiltration, percolation, actual evapotranspiration, interflow, groundwater drainage, soil moisture storage and groundwater storage. More details about these parameters and respective equations are found in WetSpa user manual (Liu and De Smedt, 2004).

2.3.4.4. Model performance indicators

2.3.4.4.1. Model bias. Model bias (*MB*) is a relative mean difference between predicted and observed stream flows, reflecting the ability to reproduce water balance (Moriasi et al., 2007). Model bias is given by the equation:

$$MB = \frac{\sum_{i=1}^{N}(Q_{si} - Q_{oi})}{\sum_{i=1}^{N} Q_{oi}} \quad (7)$$

where *MB* is the model bias, Q_{si} and Q_{oi} are the simulated and observed stream flows at time step i (m^3/s), and N is the number of time steps over the simulation period.

Model bias measures the systematic under or over prediction of a model for a set of predictions (Stockdale et al., 2011). A lower *MB* value indicates a better fit, and the value 0.0 represents the perfect simulation of observed flow volume. Model bias values tend to vary more during dry periods than during wet periods for streamflow (Gupta et al., 1999). Model simulation values can be accepted if MB is between −0.25 and 0.25 for streamflow (Moriasi et al., 2007).

2.3.4.4.2. Model confidence. Model confidence is expressed by the coefficient of determination, which is one of the important criteria in the assessment of continuous model simulation (Moriasi et al., 2007). It is calculated using:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(Q_{si} - \overline{Q_o})}{\sum_{i=1}^{N}(Q_{oi} - \overline{Q_o})^2} \quad (8)$$

where R^2 is the model determination coefficient and $\overline{Q_o}$ is the mean observed stream flow. R^2 values greater than 0.5, which are considered as acceptable (Santhi et al., 2001). R^2 is very sensitive to outliers and less sensitive to additive and proportional difference values between simulated and observed data (Legates and McCabe, 1999). Therefore, Nash-Sutcliffe efficiency is employed besides the coefficient of determination.

2.3.4.4.3. Nash-Sutcliffe efficiency. Nash-Sutcliffe efficiency (*NSE*) indicator was explored to describe how well discharges are simulated by the model and can be described as (Nash and Sutcliffe, 1970):

$$NSE = 1 - \frac{\sum_{i=1}^{N}(Q_{si} - \overline{Q_{oi}})^2}{\sum_{i=1}^{N}(Q_{oi} - \overline{Q_o})^2} \quad (9)$$

The *NSE* value can range from a -∞ to 1, with 1 indicating a perfect fit between the simulated and observed hydrographs. *NSE* is used to calibrate highly variable flow regimes characterized by extremely high and low flows. Therefore, *NSE* was found to be the best objective function for reflecting the overall fit of a hydrograph. Model simulation can be judged as satisfactory if *NSE* > 0.50 (Moriasi et al., 2007).

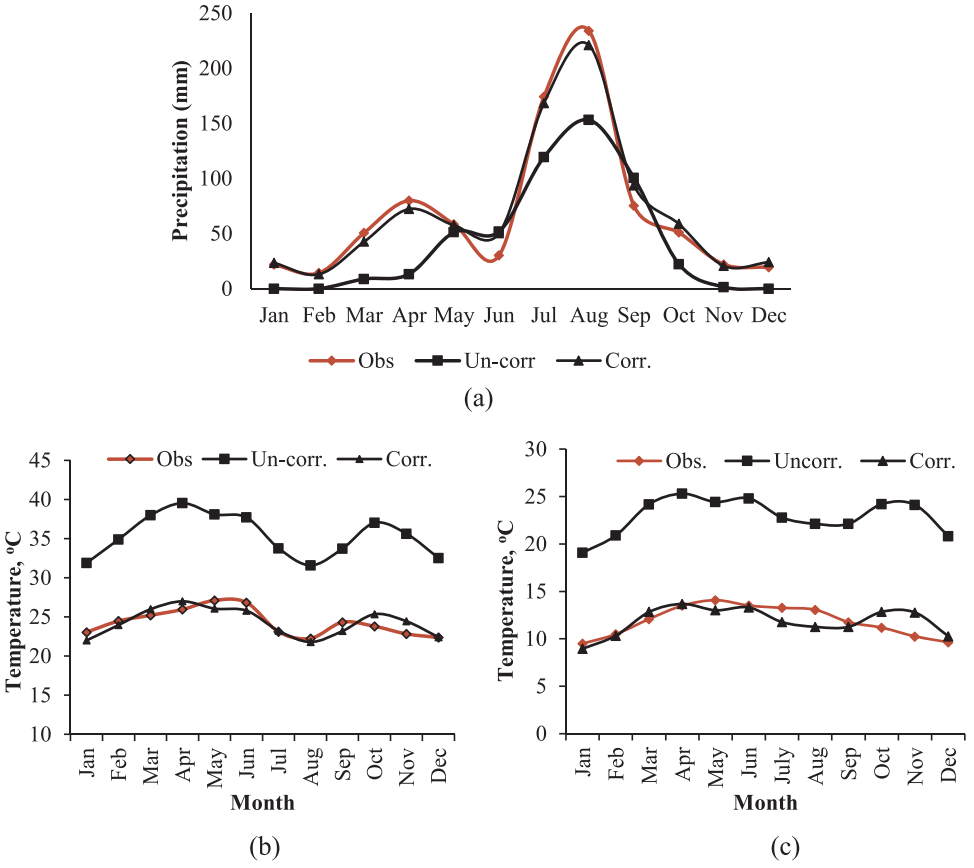

Fig. 4. Monthly bias uncorrected, corrected and observed a) precipitation, b) maximum and c) minimum temperature distribution for Mekelle station for the baseline period.

3. Results and discussion

3.1. Bias corrections

The bias corrections in monthly precipitation and temperature (maximum and minimum) of the RCP 2.6 scenario for the base period 1994–2005 are presented for Mekelle station (Fig. 4a–c). Statistical parameters indicating the corresponding uncorrected RCP and bias-corrected RCP scenarios from observation for monthly mean maximum and minimum temperatures were depicted in Table 4. The Standard Error of Mean (Mean Abs Error), Standard Deviation (Std-Error) and mean of the bias-corrected temperature data shows close agreement to the observed value. Similarly, the magnitude of bias-corrected RCP precipitation data is fitted with observed precipitation data for Michew station (Figs. 5 and 6). For other stations, the corrected RCP precipitation is found to be consistent with observed precipitation. The bias-corrected temperature data also show close agreement with the observed values.

Table 4
Performance of bias corrected method on monthly rainfall amount.

	Maximum temperature			Minimum temperature		
	Std. Error, ˚C	Mean Abs Error, ˚C	Mean, ˚C	Std. Error, ˚C	Mean Abs Error, ˚C	Mean, ˚C
Observed	2.303	0.035	24.27	2.130	0.321	11.86
RCP Uncorrected	2.797	0.053	35.36	3.520	0.042	22.90
RCP Corrected	2.303	0.035	24.27	2.130	0.322	11.86

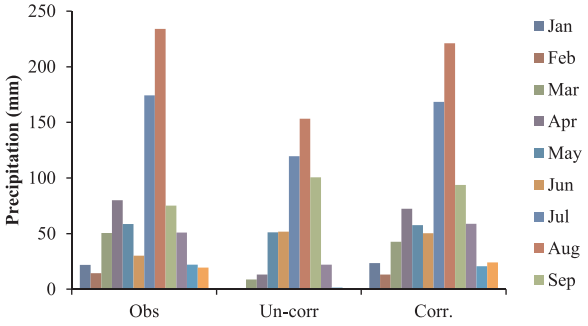

Fig. 5. Monthly bias uncorrected, corrected and observed rainfall distributions for Michew station for the baseline period.

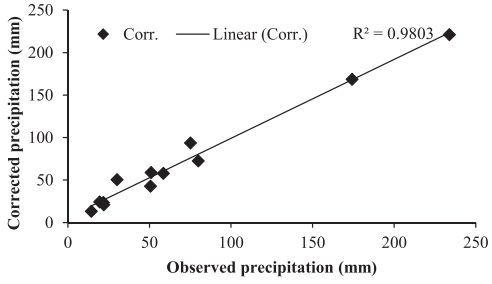

Fig. 6. Comparison between observed and bias corrected for Michew station precipitation data for the baseline period (1994–2005).

3.2. Trend analysis

Trend analysis in this study helped to compare future groundwater recharge and base flow of the catchment with climate and precipitation changes within the newly emerged RCP climate change scenarios. In

Table 5
Result of trend analysis of annual average precipitation, temperature and evapotranspiration using MK test.

Stations	Observed (1994–2013) Precipitation (mm)				Temperature (°C)				Evapotranspiration (mm)			
	S	P-value (Zs)	Sen's slope	Kendall's Tau	S	P-value (Zs)	Sen's slope	Kendall's Tau	S	P-value (Zs)	Sen's slope	Kendall's Tau
Michew	−79	0.005**	−18.7	−0.462	93	0.001*	0.034	0.544	59	0.041	2.738	0.345
Mekelle	−49	0.164**	−8.5	−0.24	−17	0.581**	−0.006	−0.099	75	0.008	3.438	0.439
Samre	−43	0.143**	−7.96	−0.251	49	0.06**	0.031	0.521	19	0.528	0.75	0.112
Mitsebri	−9	0.783**	−3.31	−0.053	71	0.013*	0.026	0.415	67	0.019	1.765	0.392
Lalibela	−21	0.489**	−2.94	−0.123	55	0.058**	0.024	0.322	45	0.125	1.366	0.263
Gonder	−37	0.211**	−11.16	−0.216	51	0.080**	0.033	0.298	1	1	0	0.006
Average			−8.76				0.023			0.287**	1.676	
Stations	**RCP 2.6 (2020–2079 Precipitation (mm)**				**Temperature (°C)**				**Evapotranspiration (mm)**			
	S	P-value (Zs)	Sen's slope	Kendall's Tau	S	P-value (Zs)	Sen's slope	Kendall's Tau	S	P-value (Zs)	Sen's slope	Kendall's Tau
Michew	−5	0.979**	−0.032	−0.003	27	0.865**	0.001*	0.016	58	0.709	0.063	0.034
Mekelle	−315	0.04*	−1.917	−0.184	25	0.875**	0.001*	0.015	65	0.675	0.097	0.038
Samre	347	0.024*	4.538	0.203	39	0.804**	0.001*	0.023	50	0.749	0.097	0.029
Mitsebri	−33	0.834**	−0.445	−0.019	77	0.619**	0.002*	0.045	56	0.719	0.064	0.033
Lalibela	5	0.979**	0.08	0.003	58	0.709**	0.001*	0.034	91	0.556	0.077	0.054
Gonder	−67	0.666**	−0.666	−0.039	65	0.676**	0.001*	0.038	−83	0.591	−0.08	−0.049
Average			−1.724				0.0012			0.667**	0.053	
Stations	**RCP 4.5 (2020–2079) Precipitation (mm)**				**Temperature (°C)**				**Evapotranspiration (mm)**			
	S	P-value (Z_s)	Sen's slope	Kendall's Tau	S	P-value (Zs)	Sen's slope	Kendall's Tau	S	P-value (Zs)	Sen's slope	Kendall's Tau
Michew	−165	0.284**	−1.527	−0.14	126	0.414**	0.004*	0.074	138	0.37	0.145	0.081
Mekelle	−266	0.083**	−1.875	−0.02	137	0.374**	0.003*	0.8	110	0.476	0.165	0.065
Samre	−247	0.108**	−3.376	−0.14	181	0.239**	0.006*	0.106	92	0.552	0.138	0.054
Mitsebri	−45	0.774**	−0.472	−0.11	172	0.263**	0.004*	0.101	204	0.184	0.333	0.12
Lalibela	−63	0.685**	−0.668	−0.11	213	0.166**	0.004*	0.124	161	0.295	0.135	0.094
Gonder	119	0.440*	1.107		180	0.011	0.003*	0.4	140	0.363	0.165	0.082
Average			−1.135				0.004			0.373**	0.18	

Note: S is an MK test statistic, Zs is MK trend test, slope (Sen's slope) is the change (mm)/annual, * and ** indicate significant and non-significant trend at 0.05 significant level, respectively. A positive value of S indicates that there is an increasing trend and vice versa.

this study, the trend was analyzed for current and future projected precipitation, temperature and evapotranspiration for the observed period of 1994–2013 and the future period of 2020–2079.

3.2.1. Precipitation

The MK test statistic for the period 1994–2013 indicates that the stations (Mekelle, Mitsebri, Miachew, Lalibela, Samre and Gonder) show a non-significant decreasing trend in precipitation (Table 5). The MK test statistic (*S*) indicates a non-significant decreasing trend for the observed and future projected precipitation for both the climate change scenarios (RCP 2.6 and RCP 4.5) except Mekelle and Samre stations (Table 5). The Samre station shows a statistically significant increasing trend in annual average precipitation (at the rate of 4.538 mm per annum), while Mekelle station showed decreasing trend at the rate of 1.917 mm per annum at 5% level of significance. The Sen's slope test also indicates the decreasing trend of rainfall for the observed period, on an average of 8.762 mm per annum over the study area. Future (2020–2079) projected rainfall again decreases by 1.724 mm/annum and 1.135 mm/annum for RCP 2.6 and RCP 4.5 scenarios, respectively for the next 60 years. This result agrees with the previous studies conducted at Gilgel Abay catchment which drains to Lake Tana (Abdo et al., 2009), climate variability in the northern part of Ethiopia (Gebrehiwot and Veen, 2013), hydro-climatic trends in the Abay/upper Blue Nile basin, Ethiopia (Tekleab et al., 2013), trend and variability of rainfall in northern Ethiopia (Hadgu et al., 2013) and IPCC (2013) using the Special Report on Emissions Scenarios (SRES) both for the current and future periods. However, Gizaw et al. (2017) have reported that the projected mean annual precipitation may increase by about 6% (9%) in the 2050s (2080s) which results in increase in stream flow by about 3% (9%) in the major Ethiopian river basins including Tekeze rivers under RCP 4.5 and RCP 8.5 scenarios. This may be due to ensembles of 10 CMIP5 GCMs average projections considered using Hydrologic Simulation Program-FORTRAN (HSPF) hydrologic model and different sources of uncertainties caused because of model uncertainty as well as Ethiopia's complex topography (Berhanu et al., 2014). The authors emphasized that more realistic climate projections could be provided using high resolutions regional climate models.

3.2.2. Temperature

The MK test provided an interesting insight about annual average temperature for the Tekeze catchment. The MK trend test for temperature shows a statistically significant increasing trend for the current (1994–2013) and future (2020–2079) climates. There is a statistically significant increasing temperature trend at Maichew and Mitsebri stations at 5% significance level (Fig. 7). The annual average temperature was found to be increasing at the rate of 0.001 °C at Michew and 0.013 °C at Mitsebri stations, respectively. However, trend results were found non-significant for Mekelle, Lalibella and Gonder stations during the observed period (Table 5). Only a statistically significant increasing trend for future projected temperature (2020–2079) was found in the case of RCP 4.5 scenarios at Gondar station (Table 5). It has also been revealed that the average temperature will increase at the rate of 0.011 °C at Gondar station. However, other stations showed non-significant increasing trends on the average annual temperature in both RCP 2.6 and RCP 4.5 scenarios (Table 5). The average temperature was found to be increasing at the rate of 0.023 °C over the observed period in the study area. Similarly, the future projected average temperature was found to be increasing at the rate of 0.0012 °C for RCP 2.6 and 0.004 °C for RCP 4.5 scenarios in the study area (Table 5). This result is in line with studies conducted in and around the basin (e.g., Gebrehiwot and Veen, 2013; Tekleab et al., 2013; Hadgu et al., 2013; Haile and Kassa, 2015; Gizaw et al., 2017). Future temperature increases could have a significant impact on the sustainability of surface water resource and groundwater recharge. This evidence is in good agreement with Yu et al. (2015), an increase in temperature along with reduced precipitation is likely to result in the loss of agricultural land due to decreased soil moisture, increased aridity, increased salinity and groundwater depletion.

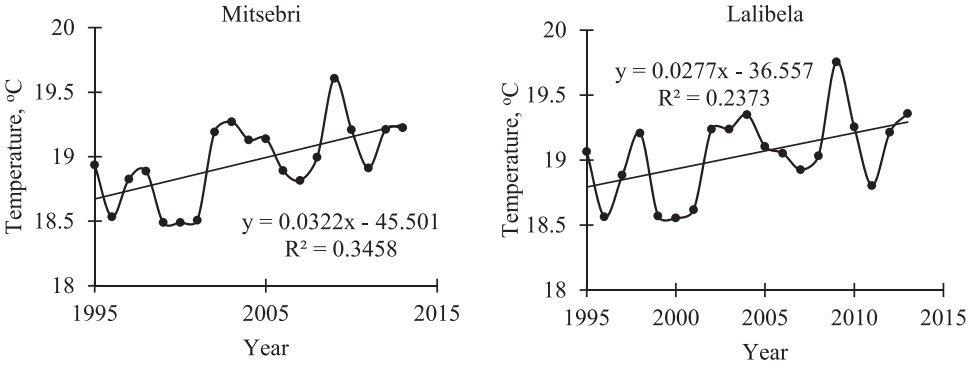

Fig. 7. Observed average temperature (1994–2013) for Mitsebri and Lalibela stations.

3.2.3. Potential evapotranspiration

The present and future potential evapotranspiration were estimated for all the six stations for RCP 2.6 and RCP4.5 climate change scenarios (Table 5). Only statistically significant increasing trend in average annual evapotranspiration was found at Michew (at the rate of 2.738 mm per annum), Mekelle (at the rate of 3.438 mm per annum) and Mitsebri stations (at the rate of 1.765 mm per annum) in the study area. However, other remaining stations did not show any statistically significant trends in annual average evapotranspiration at 5% level of significance. For observed and future evapotranspiration, the MK test shows that there is an increasing trend during the study period (1994–2013 and 2020–2079). The annual evapotranspiration was found to increase by 1.676 mm/annum during the period 1994–2013. Evapotranspiration in the study area may increase by 0.053 mm/annum and 0.180 mm/annum for RCP 2.6 and RCP 4.5 scenarios, respectively for the coming 60 years. The MK trend test showed that the change in average annual evapotranspiration for both RCP 2.6 and RCP 4.5 scenarios and observed period (1994–2013) is not statistically significant at $\alpha = 0.05$ over the study area (Table 5 and Fig. 8).

Table 6
Results of the WetSpa model calibration and validation.

Run	MB	R^2	NSE
Calibration	0	0.82	0.79
Validation	0.002	0.89	0.76
Optimum	0	1	1

3.3. Estimation of groundwater recharge and base flow

3.3.1. Calibration and validation

The model performance results during calibration and validation are presented in Table 6. The comparative analysis between observed and simulated flow have confirmed that the satisfactory model performance (Fig. 9). Table 6 reveals the presence of a good agreement between the observed and model simulated discharges values of the

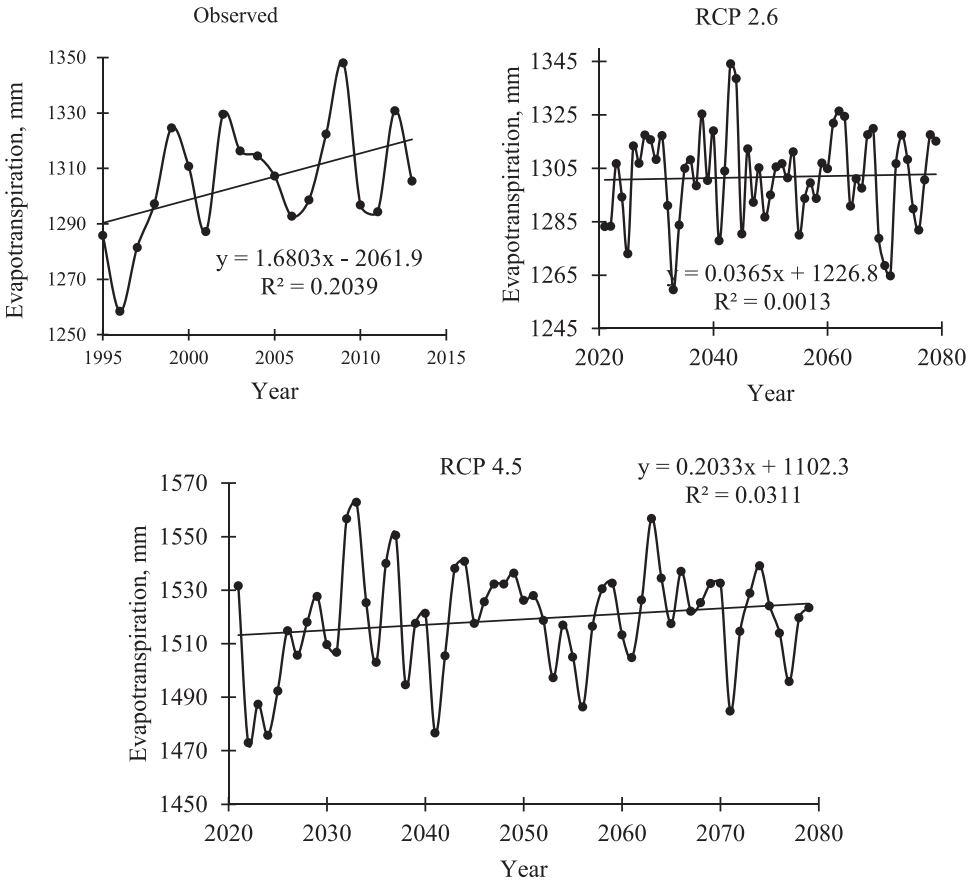

Fig. 8. Trend of average present and future evapotranspiration for the period 1994–2014 and 2020–2079.

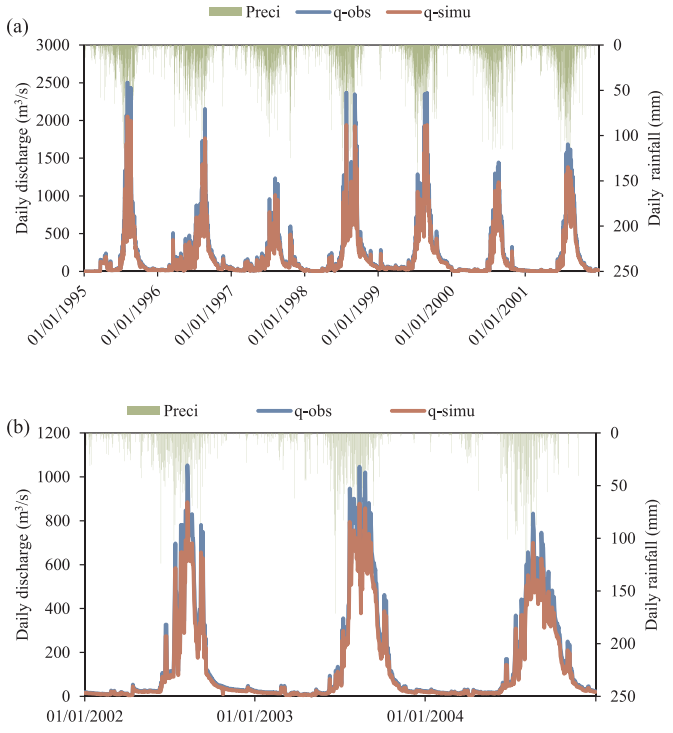

Fig. 9. Results of (a) model calibration and (b) validation hydrograph for Tekeze catchment.

catchment. The R^2 and *NSE* values are found to be 0.82 and 0.89 and 0.79 and 0.76 during calibration and validation periods, respectively. The statistical model performance indicators are found very close to their optimum best-fit values during the calibration and validation periods (Table 6). Although the model predicts the average conditions well as depicted by the statistical parameters, it does not capture the peak flow values well. This would be attributed to the inherent nature of the physical hydrological models which better predict average conditions well when compared with the prediction results for extreme cases. Extreme hydrological events are often victimized by model uncertainties which emanate from assumptions during the development of such models. Particular to this study, average values of soil moisture, flow parameters etc. were used which probably affected the model predictive ability for the peak flow events. Indeed, it is out of scope to determine watershed parameters which produce such extreme events. This model results are in agreement with Yenehun et al. (2017) where groundwater recharge was estimated in Geba basin in Ethiopia using WetSpa model.

Further, total runoff, actual evapotranspiration, groundwater recharge, interflow and soil moisture have been simulated during the simulation process (Table 7). Base flow was estimated by adding simulated interflow and groundwater flow from the WetSpa extension. During the calibration, the base flow was generated from interflow (29.5 mm) and groundwater flow (331.2 mm). The total runoff (327.89 mm) was simulated as 10% of surface flow (32.6 mm) and 90% (360.7 mm) base flow. The base flow (313.5 mm) was generated from interflow (23.8 mm) and groundwater flow during the validation period. Therefore, the total runoff was found to be 285.8 mm (Table 7). During the dry season, base flow mainly contribute to the total runoff. The recharge to the aquifers mainly occurs from precipitation and losing streams (Kebede, 2013). These model results are in good agreement with similar studies found in and around the study area (e.g., Nyenje and Batelaan, 2009; Arefaine et al., 2012; Yenehun et al., 2017).

Table 7
Summary of water balance components for the Tekeze catchment.

Water balance components	Average measured data (1995–2001) (mm)	Calibration (1995–2001) (mm)	Validation (2002–2004) (mm)
Precipitation	1050	1125.4	893.3
Surface runoff		32.6	37
Evapotranspiration	1292.22	1192.22	1320
Interflow		29.5	23.8
Groundwater flow		331.2	289.7
Base flow		360.7	313.5
Total runoff	327.89	327.89	285.8

3.3.2. Simulation of groundwater recharge and base flow

After running the calibrated WetSpa model, the current and future basic water balance components have been simulated at the outlet on a current and future time basis (Fig. 10). The simulated water balance changes for future (2020–2079) under climate change scenarios (RCP 2.6 and RCP 4.5) and baseline period (1995–2001) are presented in Table 8. The water balance components were analyzed on an annual average scale (Fig. 10a). The study result indicates that precipitation in the study area is expected to decrease by 20% for both scenarios (RCP 2.6 and RCP 4.5) (Fig. 10b and c). This result is consistent with the similar studies done by Goitom et al. (2012) in the Geba basin in Northern Ethiopia. Further, the actual evapotranspiration is projected to increase by 0.4% for RCP 2.6 and 8.1% for RCP 4.5. Similarly, the results in the Section 3.2.3 also confirmed an increasing trend in potential ET.

Consequently, the future groundwater recharge is anticipated to decrease by 3.4% and 1.3% for RCP 2.6 and RCP 4.5scenarios, respectively (Fig. 10b and c). This may occur as a result of decreasing precipitation. Moreover, the base flow value is decreased for both scenarios, with a slightly greater decrease for RCP 2.6 compared to the RCP 4.5 scenario. The annual average estimate of groundwater recharge in this study is found to be close to 50–100 mm/year (Kebede, 2013). Similarly, the surface runoff also shows decreasing trend for both emission scenarios by 15.6% for RCP 2.6 and by 19% for RCP 4.5 (Fig. 10). Moreover, Groundwater recharge and other hydrological components are found to be highly controlled by geology (Yenehun et al., 2017). Hence, the risk of annual flooding is restricted in the catchment due to the decreased future surface runoff. It can be concluded that precipitation, groundwater recharge, and base flow will decrease while evapotranspiration will increase under the climate change scenarios.

4. Conclusions

Groundwater is an important water resource and needs more attention on its vulnerability to overexploitation, pollution and, especially climate change. Therefore, this study was conducted to investigate the effects of climate change on major climatic variables and groundwater components (groundwater recharge and base flow) in Tekeze sub-catchment in Ethiopia. Precipitation indicates a negative trend for the observed and future projected scenarios. For the observed period, the rainfall decreases on average by 8.762 mm per annum over the study area and future (2020–2079) projected rainfall decreases by 1.724 mm/annum and 1.135 mm/annum for RCP 2.6 and RCP 4.5 scenarios, respectively. The average temperature shows an increasing trend at 5% significance level in both periods. Consequently, there is an increasing trend for present and future projected annual evapotranspiration.

In this study, the WetSpa model was used to simulate future water balance changes in the catchment. For both RCP 2.6 and RCP 4.5 scenarios, precipitation is projected to decrease by 20–21%. The actual evapotranspiration will be expected to increase by 0.4% for RCP 2.6 and 8.1% for RCP 4.5 which is similar to the evapotranspiration trend analysis. The future groundwater recharge will decrease by 3.4% and 1.3% for RCP 2.6 and RCP 4.5 scenarios, respectively. Base flow is

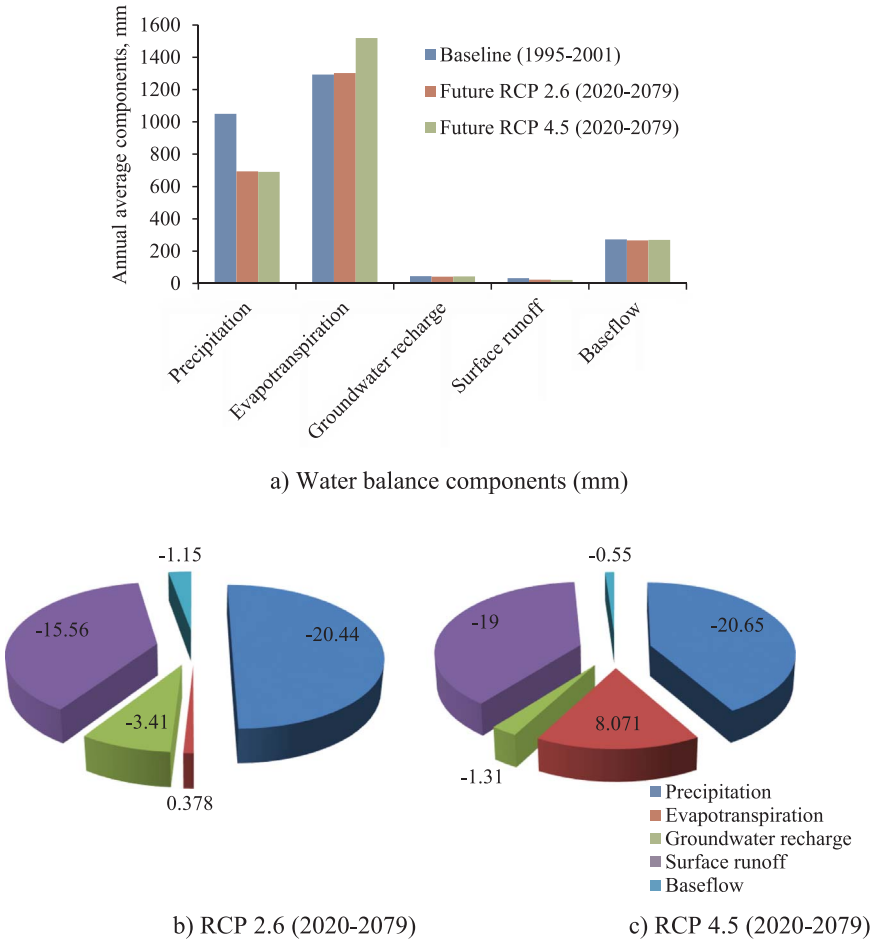

Fig. 10. Average annual a) water balance components (mm) and their future percentage changes (b&c) from baseline in the Tekeze catchment.

Table 8
Summary of annual water balance changes as compared to the baseline period.

Water balance components	Baseline (1995–2001)	Future RCP 2.6 (2020–2079)		Future RCP 4.5 (2020–2079)	
	Annual average (mm)	Annual average (mm)	Change (%)	Annual average (mm)	Change (%)
Precipitation	1050	693.54	−20.44	690.61	−20.65
Evapotranspiration	1292.22	1302	0.378	1519.12	8.071
Groundwater recharge	45.23	42.25	−3.41	44.06	−1.31
Surface runoff	32.5	23.75	−15.56	22.12	−19.00
Base flow	272.4	266	−1.15	269.4	−0.55

projected to decrease more under the RCP 2.6 scenario. Based on the study results, it can be recommended that rainwater harvesting structures and artificial aquifer recharge schemes should be implemented to enrich groundwater potential as an adaptation strategy in the study region and mitigate the possible impacts of climate change.

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